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Accuracy in estimation of timber assortments and stem distribution – A comparison of airborne and terrestrial laser scanning techniques

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ABSTRACT

Detailed information about timber assortments and diameter distributions is required in forest management. Forest owners can make better decisions concerning the timing of timber sales and forest companies can utilize more detailed information to optimize their wood supply chain from forest to factory. The objective here was to compare the accuracies of high-density laser scanning techniques for the estimation of tree-level diameter distribution and timber assortments. We also introduce a method that utilizes a combination of airborne and terrestrial laser scanning in timber assortment estimation. The study was conducted in Evo, Finland. Harvester measurements were used as a reference for 144 trees within a single clear-cut stand. The results showed that accurate tree-level timber assortments and diameter distributions can be obtained, using terrestrial laser scanning (TLS) or a combination of TLS and airborne laser scanning (ALS). Saw log volumes were estimated with higher accuracy than pulpwood volumes. The saw log volumes were estimated with relative root-mean-squared errors of 17.5% and 16.8% with TLS and a combination of TLS and ALS, respectively. The respective accuracies for pulpwood were 60.1% and 59.3%. The differences in the bucking method used also caused some large errors. In addition, tree quality factors highly affected the bucking accuracy, especially with pulpwood volume.

1. Introduction

The economic value of and detailed information on forest structure and tree quantities are crucial to individual owners and forestry organizations, enabling them to effectively plan forest management operations. Timber assortments, diameter distribution, quality and yield value are essential factors for forest owners in making decisions on forest management operations and for forest organizations, e.g. in searching for potential harvesting sites and optimizing the flow of raw materials. Incomplete or inaccurate forest information adds to the expense and challenge of forest operations (e.g. Holopainen et al., 2010).

Forest management decisions (silvicultural treatments, thinnings and final cuttings) are often made directly or indirectly, based on stand-level mean diameter, height or age, yet the most relevant attribute towards timber quality and log yield is the stem form (Kilpeläinen et al., 2011; Uusitalo, 1997; Uusitalo and Isotalo, 2005). Pre harvest measurements are mainly based on the use of field sample measurements (Uusitalo, 1997) or stem databases (Malinen, 2003). Stem form cannot be measured cost-efficiently with traditional measurements of tree species, diameters (diameter at breast height, 1.3 m, DBH, and diameter at 6 m, D6) and height used in taper curve equations (e.g. Laasasenaho, 1982). Errors in stem form predictions prevent accurate bucking simulations (Holopainen et al., 2010).

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New technologies for forest inventorying have been developed rapidly in recent decades and especially laser scanning based applications, which have already come into operational use. Airborne laser scanning (ALS) have been used to estimate forest structural parameters from the tree level (e.g. height, DBH and volume) to broader scales (stand-level mean characteristics). ALS-based forest inventory can be based on discrete or full-waveform data and either of the two main approaches for deriving forest information, an area-based approach (ABA, Næsset, 2002) and individual tree detection (ITD, Hyyppä and Inkinen, 1999). Fixed-position (mounted on a tripod) terrestrial laser scanners offer wide opportunities for three-dimensional (3D) mapping of smaller areas or individual trees with high detail. Terrestrial laser scanning (TLS) is seen as an efficient and objective option for acquiring accurate field measurement data (e.g. Liang et al., 2011; Lindberg et al., 2012) that is required e.g. in the ABA.

The estimation of timber assortments at the tree-level and DBH distributions is affected by tree detection and the tree parameter estimation accuracy. Previous studies focusing on these subjects have presented the following conclusions. Tree detection in laser scanning datasets is mostly dependent on (1) the detection algorithm used (Kaartinen and Hyyppä, 2008; Kaartinen et al., 2012), (2) forest structure (Vauhkonen et al., 2012) and (3) the density of the point clouds, resolution of the surface models interpolated, or shading (e.g. Kaartinen and Hyyppä, 2008; Kaartinen et al., 2012; Liang and Hyyppä, 2013; Liang et al., 2012; Vauhkonen et al., 2012). Kaartinen and Hyyppä (2008) and Vauhkonen et al. (2012) conducted comparison studies in which different ITD algorithms were tested. Kaartinen and Hyyppä (2008) and Kaartinen et al. (2012) concluded that the detection algorithm used showed the highest influence on tree detection. Vauhkonen et al. (2012), on the other hand, found that the success of tree detection was more dependent on tree density and canopy structure (tree clustering) than the detection algorithm. The effect of pulse density on tree detection is related to the required minimum amount of pulses per m^2, which provides an adequate level of detail for successful tree detection. Previously used densities of 5–6 pulses per m^2 are seen as prerequisites for ITD although there are studies in which trees or tree groups have been detected with pulse densities of about two pulses per m^2 (e.g. Breidenbach et al., 2010; Vastaranta et al., 2011). Kaartinen and Hyyppä (2008) concluded that the improvement in tree detection was minimal when pulse density was increased from two pulses/m^2 to eight pulses/m^2.

The factors affecting tree detection and parameter estimation also vary depending on the laser scanning technique (ALS or TLS) used, due to the difference in view perspective. ALS data are collected above the forest canopy looking down and TLS data are collected below the canopy with a moving view angle (vertically from 25° to 335°). It should be noted that TLS cannot provide the same spatial coverage as can ALS. ALS tree detection accuracies have varied between 25% and 102% (e.g. Brandtberg et al., 2003; Kaartinen and Hyyppä, 2008; Kaartinen et al., 2012; Leckie et al., 2003; Persson et al., 2002; Popescu et al., 2003; Vauhkonen et al., 2012; Yu et al., 2011). A large error source in ALS-based tree detection is the proportion of understorey trees that are not visible in the ALS data. Persson et al. (2002) showed that 71% of the trees that were detected represented 91% of the total volume in the study area. Visibility is also an important factor when TLS is used to detect trees. TLS data can be collected with single-scan or multi-scan modes. Tree detection accuracy is significantly higher with the multi-scan mode, because all gaps caused by tree shading are covered. Previously 91.7–100% tree detection accuracies have been reported, based on multi-scan mode and 55.3–90% with single-scan mode, depending on the tree density in the study areas (Liang and Hyyppä, 2013; Liang et al., 2012; Maas et al., 2008).

The tree parameter estimation methods that can be applied differ depending on the laser scanning technique used. In ALS only tree height can be measured, while all the other parameters (e.g. DBH and volume) are modelled based mainly on the measured tree height and crown diameter. With TLS, it is possible to directly measure diameters from different heights and form a stem curve (Kankare et al., 2013; Liang et al., 2014; Pfeifer and Winterhalder, 2004). Based on the stem curve measured it is possible to calculate the volume without the use of models (Liang et al., 2014). DBH estimation accuracies derived from ALS data have varied between 1.25 cm and 3.9 cm, depending on the method and study area (e.g. Maltamo et al., 2009; Vauhkonen et al., 2010, 2013, Yu et al., 2011). The DBH measurements using TLS data have been more accurate at the tree level. Previously DBH measurement accuracies have varied from 0.74 cm to 2.41 cm (Kankare et al., 2013; Liang and Hyyppä, 2013; Liang et al., 2014; Vastaranta et al., 2009). Liang et al. (2014) used an automated stem curve measurement, showing that higher accuracies can be achieved with automatic than manual measurements from TLS point clouds.

Stem total and assortment (saw log and pulpwood) volumes and their estimation accuracies have previously been reported mainly at the forest stand level (m^3/ha) (Holmgren et al., 2012; Korhonen et al., 2008; Peuhkurinen et al., 2007, 2008). Although the studies by Peuhkurinen et al. (2007) and Holmgren et al. (2012) aggregated those estimates from individual tree segments, as far as we know, no studies validating log and pulpwood proportions at the tree level are currently available. Tree-level total volume estimation has been widely studied (e.g. Kankare et al., 2013, Liang et al., 2014; Maltamo et al., 2009; Yu et al., 2011). Table 1 presents a range of tree-level volume prediction accuracies obtained earlier in forest conditions similar to our study area.

The objective of the present study was to compare the accuracies of high-density laser scanning techniques (ALS and TLS) to estimate stem diameters and both total and assortment volumes. TLS and ALS techniques have been widely studied in the last one and half decades but there has been an increasing demand from the forest industry on comparison of these two techniques in timber assortment volumes estimations. The study also introduces a new method combining the TLS and ALS techniques for more detailed tree mapping, which could also be a viable option for forest mapping in larger areas. The results of the study constitute important steps towards operational wood procurement planning and are of high current interest in forestry organizations.

2. Material and methods

2.1. Study area and field measurements

The study area (Fig. 1) was located in Evo, southern Finland (61.19°N, 25.11°E). The area belongs to the southern Boreal Zone and comprises approximately 2000 ha of mainly managed forest. The study site was a forest stand of about 2 ha and the main tree species was Scots pine (*Pinus sylvetris* L.). The site type of the stand was the Myrtillus type (medium-rich mineral soil forest). The mean age of the pine trees was approximately 75 years and the forest management history included thinnings and two fertilizations. Traditional field measurements were conducted for 144 trees selected from the stand. The trees were marked and numbered in the field and the DBH was measured with steel callipers from two directions perpendicular to each other. The tree height was measured with a Haglöf Vertex laser rangefinder (Haglöf Sweden AB, Långsele, Sweden). The mean height and DBH of the sample trees were 24.8 m and 298.3 mm, respectively. More detailed statistics of the sample trees are presented in Table 2.